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S.M. Berman
Building Technologies Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

G. Fein
Neurobehavioral Laboratory Software
41 Rhinestone Terrace
San Rafael, CA 94121

D. Jewett, B. Benson, T. Law, A. Myers
Abratech Corporation
475 Gate Five Road, #255
Sausalito, CA 94965

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Luminance Controlled Pupil Size Affects Word Reading Accuracy

S. Berman, G. Fein[1], D. Jewett[2], B. Benson[2], T. Law[2], A. Myers[2]

Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

[1]Neurobehavioral Laboratory Software
41 Rhinestone Terrace
San Rafael CA 94121

[2]Abratech Corporation
475 Gate Five Road, #255
Sausalito CA 94965

Abstract

The present study extends our prior visual performance studies to a complex resolution task which is representative of tasks in typical workplace environments: word reading presented at a fixed high contrast (black print on white background), but with varying sized letters.

We examined the effect of pupil size on the letter size-acuity function using accuracy of word recognition as the endpoint. Word reading acuity has been extensively used in vision research as a measure of visual performance and has been shown to correlate well with face recognition and other complex recognition tasks. In this study, the task was shielded from the surround lighting, allowing the luminances of the surround and task to be controlled independently. Two pupil size conditions were compared, where pupil size is controlled by high or low luminance levels of a single surround illuminant. We chose to use a single illuminant to control pupil size to avoid changes in induced color which occur when pupil size is changed by varying the surround spectrum.

The results here for nine subjects, ages 23 to 59, years replicate and extend our prior visual acuity studies using Landolt C tasks, and show again that smaller pupils improve visual performance even though task retinal illuminance is substantially reduced. We also found that improvement in visual performance with smaller pupils occurs despite an increased disability glare under the high luminance surround condition. Our results are directly applicable to self-illuminated tasks (e.g., computer terminals) operating with black print on a white background.

Introduction

In previous studies[1,2] we examined the effect of pupil size on orientation recognition of a Landolt C in a paradigm with fixed task size and variable task contrast. In those studies, pupil size was controlled by adjusting the spectrum and/or the intensity of the surrounding luminance. For young adults, a 40% decrease in pupil area was associated with about a 33% improvement in threshold contrast. Elderly subjects with at least 20/30 vision showed improvements in threshold contrast of a similar magnitude, even though they had, on average, a smaller decrease in pupil area (approximately 28%). These performance improvements in recognition were obtained even though task retinal illumination was decreased substantially (in proportion to the change in pupil size). It is important to emphasize that the performance was better even though the retinal illumination was decreased, since a naive approach to lighting assumes that performance must decrease if retinal illumination decreases. Thus, these results demonstrate the role of pupil size on visual performance when light levels are photopically adequate. Under these lighting conditions, the quality of the eye's optics has been claimed to be limiting factor in visual performance[3]. Our working model is that the deleterious effect on visual performance of many optical system aberrations can be reduced with smaller pupils. Moreover, the resultant improvements in performance due to decreased pupil size occur even in the presence of substantial reductions in task retinal illuminance.

The present study extends our prior visual performance studies to word reading tasks presented at a fixed high contrast (black print on white background), but with varying character size. Word reading is a complex resolution task which is representative of tasks in typical workplace environments. As (letter) size decreases toward threshold levels, word reading accuracy diminishes, providing a metric region whereby the effects of pupil size can be measured.

In this study, we examine the effect of pupil size on the word-reading acuity-function. Word reading acuity has been used in vision research as a measure of visual performance and has been shown to correlate well with face recognition and other complex recognition tasks. In this study, the task is shielded from the surround lighting, allowing surround and task background luminance to be controlled independently. Two pupil size conditions are compared, where pupil size is controlled by high or low luminance levels of a single surround illuminant. We chose a single illuminant to control pupil size to avoid any changes in induced color which occurs when pupil size is changed by varying the surround spectrum. (Subsequently we have shown that there is no induced-color effect on Landolt C performance.[4])

The results here replicate and extend our Landolt C studies and show again, that smaller pupils improve visual performance even though task retinal illuminance is markedly reduced. The improvement in visual performance with smaller pupils more than compensates for the increased disability glare present in the high luminance surround condition.

Methods

Subjects

Seven female and two male subjects obtained by advertising in a local newspaper were studied. They ranged from 23 to 59 years of age (mean ± s.d. = 35.5 ±9.8 years). Eight of the subjects had no vision correction (did not use spectacles) while the ninth wore contact lenses. No refractions were done, but all subjects were determined to have Snellen acuity of better than 20/30, as tested.

Reading Chart Specifications

The words to be read and identified were presented on rectangular charts. These reading charts were created using a method similar to that of Bailey and Lovie[5]. Twenty-four unique reading charts were made, each having ten lines of words with six words per line printed in a fixed point-size Times-Roman font. The letter size decreased from line to line, with a factor of two decrease over six lines. There were six words on each line in no particular order: two four letter words, two seven letter words, and two ten letter words. For the subject distance of 1.25 m from the task the top line was 20/25 (0.10 logMAR), and the last line was 20/8.9 (-0.35 logMAR). This range of type sizes was chosen in the hope that every subject would be able to read the first line, while no subject would be expected to read the final line. The charts were printed on clear transparencies using a Linotype 330 printer at 2540 dpi resolution. Figure 1 shows a typical chart.

The reading chart words were chosen from commonly encountered words in a spell-checker dictionary[6]. Words were not put together that would form phrases or had connected meanings. No special attention was given to the relative occurrence of the chosen words in the English language. Since the study was a comparison of accuracy of reading the words under two different surround lighting conditions, we assumed a strictly common level of familiarity of the chosen words should not be important.

Task Lighting

The charts were mounted at the front of a wooden box that contained three 25W frosted tubular incandescent lamps. The interior of the box was covered with aluminum foil. Three layers of semi-opaque white plastic and an IR absorbing filter were placed between the light source and the charts to diffuse the light. The IR filter was included to reduce task lighting interference with the function of the IR pupillometer. The incandescent lamp voltage was controlled by a Variac, which allowed experimental control of task luminance. From the position of the subject, the backlit area of the box (14 cm by 18 cm) subtended a visual angle of 6.4 degrees horizontally by 8.2 degrees vertically. This sizing allowed at least 1.25 cm of illuminated area around the perimeter of the reading chart. Variation of luminance across the backlit area was less than 10%. The remaining perimeter of the viewed task surface was a black border surrounding this backlit task area, with a vertical extension of 2.5 cm and horizontal extension of 6.4 cm. The task surface was protected from surround light by a black shield extending out 40 cm from the task box. The entire black area surrounding the illuminated portion of the task subtended 6.0 degrees vertically and 5.6 degrees horizontally. Subjects sat in a comfortable chair at a distance of 1.25 m from the task (see Figure 2).

Surround Lighting

The experimental room had dimensions 2 m by 2 m, with a 2.2 m height, and with walls and ceiling painted with a spectrally flat white paint (Kodak). Surround lighting was supplied by indirect illumination of the room by one F40T12 Sylvania fluorescent lamp coated with Sylvania #213 phosphor, which has its spectral peak output at about 510 nm. We chose the F213 lamp, with its scotopically enhanced spectrum, in order to achieve pupil sizes that are in the range of typical interior values, but with a minimum of possible indirect photopic luminance effects of the surround lighting on the task (see discussion). The lamp fixture was located directly above, but shielded from the subject's head, 1.4 m from the front wall and 0.5 m below the ceiling[7]. Luminances were measured using a Pritchard Spectrophotometer (Model 1980A), at a point on the front wall approximately 1 m off the floor and 0.5 m from the left wall. Luminances varied on the front wall by about 10%. Figures 2 and 3 show a photograph and a sketch of various room components, respectively.

Pupil Size Recording

Pupillometry was accomplished by the use of an ASL 4250R Eyetracker/Pupillometer[8] with pupil data recorded continuously during the reading session. The instrument measures point of gaze and pupil diameter (horizontally across the pupil), at a sampling rate of 60 Hz. The ASL PC-EYENAL (V. 2.1) software package was used to remove blinks and then to determine the fixation points and pupil diameter at each fixation point as subjects read each chart. The pupil diameter was then averaged for all fixation points (weighted for fixation duration) to give an average pupil diameter for each chart read.

Experimental Procedure

Subjects were seated in the experimental chamber and familiarized with the equipment in the room. The Eyetracker focus and positioning was then adjusted and calibrated for reliable point-of-gaze measurements. Subjects were then given the following instructions:

> "Please start reading aloud the words at the top of the list, reading across each line. Please try not to read the words until I tell you to start. Please speak clearly and fairly loud. I may ask you to stop and repeat a word if I can't tell what you said. When you reach the end of a line, start the next one. Feel free to stop on a word and look for as long as you'd like, but once you've passed a word, don't go back to it. If you can't read the whole word or are uncertain, make your best guess. If you feel like you can see the word, but don't know what it means or how to pronounce it, try to spell it or pronounce it as best you can. When you feel like you can't read the words anymore, stop and tell me "I'm done." Please try not to squint, just keep your eyes open and look carefully. Don't lean forward to get a closer look. I'm not interested in how good you are at reading the words - what is important to me is that you read the words with the same method throughout the experiment. If you want to stop and take a break between charts, let me know and we'll take a break."

The subject was then shown a chart similar to, but with significantly larger type sizes than those used in the study proper, and was asked to read it. This allowed us to answer any questions about how the task was to be performed before the test charts were run.

Each subject was studied under six different lighting conditions: two levels of surround luminance (5 and 50 cd/m^2 F213) with three levels of task luminance (20, 50, and 80 cd/m^2.) Subjects initially read two charts under each of the lighting conditions, with lighting conditions and chart order randomized across subjects. The subject was asked to relax with their eyes open for a period of two minutes before reading each chart to achieve adaptation to the lighting condition. Subjects were asked if they experienced fatigue; subjects who were not fatigued were continued on through one or two more charts for each of the lighting conditions.

In spite of the black shield which extended out from the task to prevent the incursion of surround lighting, it was determined by measurement after subject data was taken that some proportion of the surround lighting fell on the task, increasing the direct task background luminance by 1.8 cd/m^2 for the high surround condition and 0.18 cd/m^2 for the low surround condition. In addition to this direct light veil caused by the incursion of surround lighting on the task, there was an ocular veil resulting from the effect of surround light scatter in the eye. The magnitude of this ocular veil is also proportional to the surround luminance. This equivalent veiling luminance resulting from the effects of surround light scatter in the eye, was determined by integrating the expression given by Vos[9] over the angular subtense of the surround field, and was found to be 5% of the surround luminance, i.e., 2.5 cd/m^2 and .25 cd/m^2 for the two surround conditions. After correcting for both of these sources of additional task adaptation luminance, the resulting task background luminances were 20.4, 50.4, and 80.4 cd/m^2 for the 5 cd/m^2 surround lighting condition, and 24.3, 54.3, and 84.3 cd/m^2 for the 50 cd/m^2 surround lighting condition. This inequality of luminances for the two surround lighting conditions made the original balanceddesign unbalanced, necessitating a more complex statistical analysis then originally planned (see below). Additionally, because of the presence of these veiling luminances the task contrast for the two surround conditions were not equal, the subjects actually having less task contrast for the high surround condition than in the low surround condition. No attempt was made to correct for this difference of contrast conditions (see discussion section below).

The subjects' reading of the charts was recorded on a micro cassette recorder. After all the charts were read, the audio tape was reviewed by a second experimenter other than the one who conducted the trial, to determine the number of words read correctly on each chart. The second experimenter was unaware of the lighting and task conditions under which the charts were read. A word was considered correctly read if 2/3 of the letters were identified.

Data Analysis

Prior to statistical analysis, for each subject, pupil size and reading accuracy data were averaged across charts for each of the six task lighting by surround lighting conditions. Each dependent variable (average pupil size and average number of words read per chart) was then analyzed using a repeated measures Analysis of Variance design with six repeated measures (two surround luminances by three task background luminances) per subject. As noted above, light scatter in the eye and leakage of surround lighting onto the task resulted in different task background luminances at the two surround lighting levels (i.e., the design had unbalanced rather than fully crossed experimental factors). This necessitated the use of the BMDP-5V program which uses structured covariance matrices to analyze unbalanced repeated measures Analysis of Variance designs[10]. Using this program, the unbalanced factors (the task luminances) were analyzed as covariates which varied across the repeated measures. Both linear and quadratic effects of task background luminance on the dependent variables were estimated. Quadratic effects were the highest order model-free characterization of these effects possible, given that there were only three levels of task background luminance measured.

The reading accuracy data were also analyzed a second time as a function of surround luminance and task retinal illuminance (i.e., effective Trolands). For each subject, for each of the surround lighting by task background lighting conditions, effective task retinal illuminance was computed from the subjects' average pupil size and specific task background luminances, adjusting for the Stiles-Crawford effect. Note that the task background luminance values used in this retinal illuminance computation had already been adjusted for light scatter in the eye and for leakage of surround lighting onto the task.

Results

Pupil Size

The pupil size data as a function of surround and task background luminance are presented in Figure 4. There was a decrease in pupil size as surround luminance was increased from 5 to 50 cd/m^2 (χ^2[1 df] = 47.71, $p < 0.0001$), with the average subject's pupil area decreasing on average by 8.1 mm^2 (s.e. = 0.79 mm^2) to the mean value 10.0 mm^2 in the high surround condition for the average level of task background luminance. There was a strong trend toward a significant interaction effect on pupil size, of task background luminance combined with surround luminance (χ^2[1df] = 3.41, $p = 0.065$). This interaction was due to the pupil size effect of task background luminance that was present only under the low surround luminance conditions (see upper data points in Fig. 4). This interaction was statistically significant for low surround condition (χ^2 [1 df] = 42.37, $p < 0.0001$), but not significant for the high surround condition (χ^2[1 df] = 1.40, $p = 0.24$).

Reading accuracy as a function of task background luminance

The reading score data as a function of task background luminance and surround luminance are shown in Figure 5. The score data shows a nearly linear increase in accuracy of about 2 words as the task background luminance increases from 20 cd/m^2 to 50 cd/m^2 followed by a leveling off as the task background luminance reaches 80 cd/m^2. There was a non-significant interaction effect between task background luminance (both linear and quadratic components) and surround luminance on reading score (p-values were > 0.41 for both linear and quadratic task background luminance by surround luminance effects). This means that the fits of reading score as a function of task background luminance were essentially parallel for the two levels of surround luminance. There were highly significant linear and quadratic effects of task background luminance on reading score (χ^2 [1 df] = 28.26 and 14.34), respectively, both p's < 0.0001). There was also a significant effect of surround luminance on reading score (χ^2 [1 df] = 6.07, p = 0.014), with the average subject reading 0.85 more words (s.e. = 0.35 words) in the high surround condition for a given level of task background luminance.

Note that the quadratic fits shown in Fig. 5 show a slight downturn at the highest level. This is due to the quadratic modeling, which is the best permitted by only three data points. We would not extrapolate the downturn to additional data at still higher task background illuminances.

Reading accuracy as a function of retinal illuminance

The reading score data as a function of effective task retinal illuminance and surround luminance are shown in Figure 6. The score data shows behavior similar to the case above, but exhibits a larger difference between the two surround conditions. There was a non-significant interaction between effective retinal illuminance (both linear and quadratic components) and surround luminance on reading score (p-values were > 0.64 for both linear and quadratic task background luminance by surround luminance effects). We interpret this to mean that the plots of reading score as a function of retinal illuminance were essentially parallel for the two levels of surround luminance. There were highly significant linear and quadratic effects of effective retinal illuminance on reading score (χ^2 [1 df] = 50.16 and 21.80, respectively, both p's < 0.0001). There was also a highly significant effect of surround luminance on reading score (χ^2 [1 df] = 30.49, p < 0.0001), with the average subject reading 2.00 more words (s.e. = 0.36 words) in the high surround condition (smaller pupil) for a given level of retinal illuminance.

Association between the effects of surround luminance on pupil size and on reading accuracy

We computed the correlation over subjects of the average pupil size change vs. the average reading accuracy change as surround luminance changed from 5 to 50 cd/m^2. The correlation value was 0.59 (p = 0.09), indicating that, as the surround luminance was increased, subjects with the largest pupil size decreases tended also to have the largest acuity score increases. However, this tendency was not sufficiently robust to reach statistical significance and needs to be replicated in a larger number of new subjects. Figure 7 shows a plot of score difference (averaged over task luminances) versus pupil size difference for the nine subjects.

Discussion

In this study, pupil size was controlled by varying the luminance level of the surround, which covered the visual field beyond the central 21 degrees. There was a highly significant improvement in reading accuracy with smaller pupils. The effect of smaller pupils on reading acuity more than compensated for the decrease in retinal illuminance caused by the smaller pupil. Thus, increased retinal luminance was not associated with improved acuity, establishing that such a relationship may not exist at typical photopic light levels.

We have demonstrated in a previous study[1] that about the same pupil size differences as occurred in the present study can be obtained by using two different lamp spectra at a fixed surround photopic luminance, one spectra scotopically-enhanced (smaller pupils), and the other scotopically-deficient (larger pupils). In the present study we chose a single lamp to provide the surround illumination at two photopic levels to eliminate the possible alternative interpretation that increased acuity resulted in whole or in part from surround-induced task-color differences due to the different surround spectra.

This study demonstrates again, as we found previously in studies of Landolt C recognition[1,2] that the increased task retinal illuminance associated with the larger pupil does not compensate for the decreased acuity due to increased pupil size. For the larger pupil, task retinal illuminances were typically 80% higher than for the smaller pupil, but yielded less reading accuracy. These results indicate that both pupil size and retinal illuminance are important in the determination of visual acuity, and that under some conditions pupil size effects predominate.

Our hypothesis is that the improvement in reading accuracy when the surround luminance changes from 5 cd/m^2 to 50 cd/m^2 is due to the observed decreases in subjects' pupil sizes. This improvement occurs in spite of two confounding factors previously mentioned in the Methods section that combine to make the task at the higher surround luminance condition (smaller pupils) more difficult than in the low surround condition. First, there is a small fraction (3.6%) of the surround light that manages to incur on the task and second, there is the ocular veiling luminance caused by surround light scatter in the optical media of the eye. Both of these effects are 10 times larger for the high surround condition since they are proportional to the surround luminance, and add together to reduce the effective contrast of the task for that condition. For example, at the lowest task background luminance of 20 cd/m^2, task contrast at the high surround condition is reduced from nearly 100%, to 82%. When the task size reaches criticality such reductions in contrast can increase task difficulty, reducing the pupil size acuity benefit. Nonetheless, our results showed that the pupil size effect was sufficiently robust to yield a significant difference in reading accuracy even in the context of these countervailing effects. Were we able to control or eliminate these countervailing effects, the pupil size effect or word reading acuity would likely be larger than the 1-word increase we measured.

Several studies have shown improvements in acuity associated with increases in task luminance,[11-13] as is also shown here, e.g., Figure 5. However, in those studies pupil size was not controlled and the observed acuity improvements could have been partly a result of the decreasing pupil size caused by increasing the task luminance which was also the surround luminance. Some data on pupil size was provided in those studies and in all three studies, the results showed a decrease in pupil size associated with the increasing task/surround luminance. In view of our results here we believe it is likely that the increases in acuity of these studies were due, at least in part, to the pupil size effect and were not solely a result of increased retinal illuminance. More recent studies[14] have shown that pupil size can affect grating acuity, which is improved with smaller pupils.

For each of the two pupil size conditions, our results (Figure 5) are qualitatively similar to those of Shlaer[15] who demonstrates, for two subjects with fixed 2 mm diameter pupils, a slight continuing rise in Landolt C acuity with increasing task luminance over the same range of luminances as our task luminance variation. A question remains as to whether the performance difference for the two pupil sizes here observed would be maintained at still higher task luminances.

Shlaer[15] also measured grating acuity for fixed 2 mm pupils and found that it saturated in the range of luminances of our study, as compared to Landolt C acuity, which did not saturate. We did not extend the range of task luminances in the present study to examine possible saturation of reading accuracy with increased task luminance. It is possible that the continued slight increase in Landolt C acuity (rather than saturation) observed by Schlaer is due to a task artifact. The orientation of the C can be established without actually recognizing the gap per se, but instead by observing a contrast variation over the C surface due to the presence of the gap. Several of our observers have noted this effect. With such a shift in criterion the task may not be simply defined by the gap size, and apparent recognition may be accomplished by a sensitivity to a contrast gradient rather than an actual true recognition of the gap. Thus, the question as to whether performance or acuity saturates at different task luminance values (which could also depend on pupil size) needs further investigation.

In a separate replication study[4] we have investigated whether the pupil size effects that affect a Landolt C recognition task are observed if subjects were accurately refracted. Effects of similar magnitude as previously reported in our earlier study of Landolt C recognition[1] were observed even in subjects with perfect eyesight (to the limit of a standard optometric examination). These results indicate that the pupil size effects observed here are likely to have been observed if we had corrected our subjects' vision for possible refractive errors.

We have also investigated whether our previous results[1] demonstrating improved performance on Landolt C recognition might be due to the use of the greenish tinted F213 lamp, as the provider of surround illumination, as was the case in the present study. This (as yet unpublished) replication study used a daylight fluorescent to provide surround illumination and the results obtained confirmed our previous results that smaller pupils were associated with improved performance. Thus, we believe that the results obtained in the word reading study are not specific to the F213 surround spectrum.

Because our study was a within-subject comparison of word reading acuity, the selection of words used, although not precisely based on standard methods of word occurrence or familiarity in the English language, should not influence the results[16,17]. None of the subjects reported that the words were totally unfamiliar.

This study has an advantage over our previous studies in identifying the underlying mechanisms of the effects of pupil size on visual performance. In the previous studies the task was the recognition of the orientation of a Landolt C where the C is viewed by way of a front faced mirror directed at a video-display terminal (VDT), with the task guarded by a black tube that prevents the room lighting from impinging on the task. Because in these studies we did not control for subjects fixation, it is possible that during the course of performing the task subjects' could have inadvertently shifted their view from the VDT task to the mirror edge, to the black curtain surrounding the mirror, or to the guard tube edge. If at the instant of C presentation subjects were fixated elsewhere, then the performance results could have been due to the better depth of field associated with smaller pupils rather than due to an acuity improvement. On the other hand, in the word reading task reported here, subjects, of necessity, were accommodating for the task as they read the test words. Thus, we propose that the effects observed here are likely to be due to an improvement in acuity resulting from the smaller pupils, rather than from a depth-of-field effect.

The results of this study and our previous study of Landolt C recognition demonstrate that for values of task luminance typical of building interiors, acuity and contrast sensitivity are improved with smaller pupils. These results are obtained for subjects ranging in age from 20 to 70 years and with at least 20/30 vision. Since the spectral response of pupil size is dominated by scotopic sensitivity,[7] specification of light levels solely by use of the photopic response leaves the lighting practitioner with an inadequate predictor of visual function. This inadequacy is further exacerbated by the results of our study on perceived brightness which show a major scotopic contribution to brightness perception in full field conditions[18]. Taken together these studies imply that conventional photometry needs to be supplemented. This enhanced photometry should allow lighting practice to more adequately include the effects of lighting on human vision in realistic conditions. Such an enlarged concept of photometry will permit a more energy-efficient lighting economy.

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Discussions

The authors have once again demonstrated that pupil size can affect visually directed performance with smaller pupils resulting in improved performance -- in this case in spite of increased disability glare. Rather than resorting to a somewhat complex statistical analysis with all its assumptions, it might have been far simpler to do the obvious control experiment -- use a physical or optical artificial pupil to replicate the results. This would also have solved the questions about refractive state (a diffraction limited system could be chosen).

The authors chose subjects who wore no optical correction (not the same as not requiring a correction). Indeed, those over the age of 50 would almost certainly be seriously ametropic at 1.25 meters if they were emmetropic at 6 meters. Because the data are averaged across all subjects, one cannot tell from the paper if there are subject specific effects, but the large differences among subjects shown in figure 7 may indicate such age effects (if the heart and diamond are older subjects). The authors may wish to comment on this.

As has often been the case, the authors have provoked all of us to reassess our preconceived notions about visual performance and should instigate a flurry of research in an attempt to replicate their findings and confirm their hypotheses.

Alan L. Lewis, O.D., Ph. D.
Ferris State University
College of Optometry

Authors' response

To A.L. Lewis

We feel that the use of artificial pupils is not desirable for these experiments, because of the difficulty in centering the artificial pupil in naive subjects and the value of demonstrating that the effects are due to pupillary responses to lighting effects. Furthermore, in this study we were able to demonstrate the pupil size effect in the presence of increased disability glare of the surround, which worked to oppose our hypothesis. This would not be the case with artificial pupils.

Our other study (this issue) has shown that the visual performance effects can be observed in correctly-refracted subjects but are greater when vision is blurred. Our lack of data on the refraction of the subjects in this work could lead to an unintentional bias due to inclusion of data from subjects' imperfect refractions, but we do not consider that such a bias would be the only explanation for the effects seen. In our future research we intend to document the refractive state of all subjects.

Concerning the question of age effects in Fig. 7, the ages associated with the heart and diamond were 32 and 36 years, respectively. In general, data of Fig. 7 did not show any correlation with age. Our previous study of Landolt C recognition in elderly subjects[2] showed that even though pupil size changes were smaller than young adults, the changes in visual performance were comparable.

We hope, along with Dr. Lewis, that others will replicate our experiments, or otherwise test our hypotheses.

Fig. 1

Point Size, (Snellen Acuity), Character Size, Angle	Words
14.1 pts., (20/29), 2.49mm, 6'51"	lantern downstairs farm gang everything lawsuit
12.6 pts., (20/25), 2.22mm, 6'6"	tobacco duck expressway fame tonight fastidious
11.2 pts., (20/23), 1.97mm, 5'25"	gravestone trample flag grindstone treetop fuss
10.0 pts., (20/20), 1.76mm, 4'50"	noticeable mice welfare optimistic move acrobat
8.9 pts., (20/18), 1.57mm, 4'19"	asphalt parliament mutt oven assault pincushion
7.93 pts., (20/16), 1.4mm, 3'51"	peep profession begging pick canteen redemption
7.07 pts., (20/14), 1.24mm, 3'25"	copy tedious commission democratic dead texture
6.29 pts., (20/12), 1.11mm, 3'3"	gust various infectious janitorial vagrant hang
5.61 pts., (20/11), 0.99mm, 2'43"	network locomotion melt noon nourish managerial
5.0 pts., (20/10), 0.88mm, 2'25"	jackpot dusk dinnertime kingdom even distortion

Figure 1: Example of the word reading charts. Actual charts used contained only the words, the point size information was omitted. The space between each word is equivalent to two character spaces.

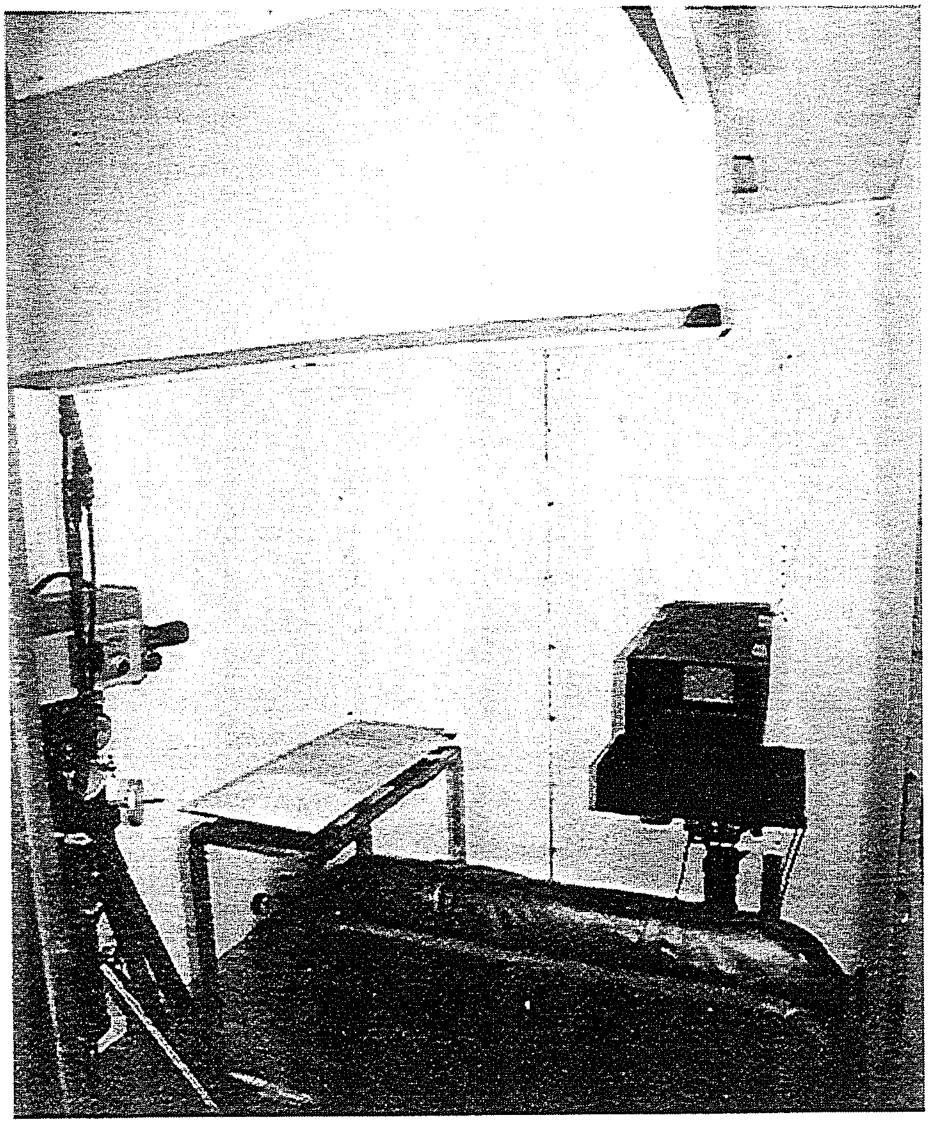
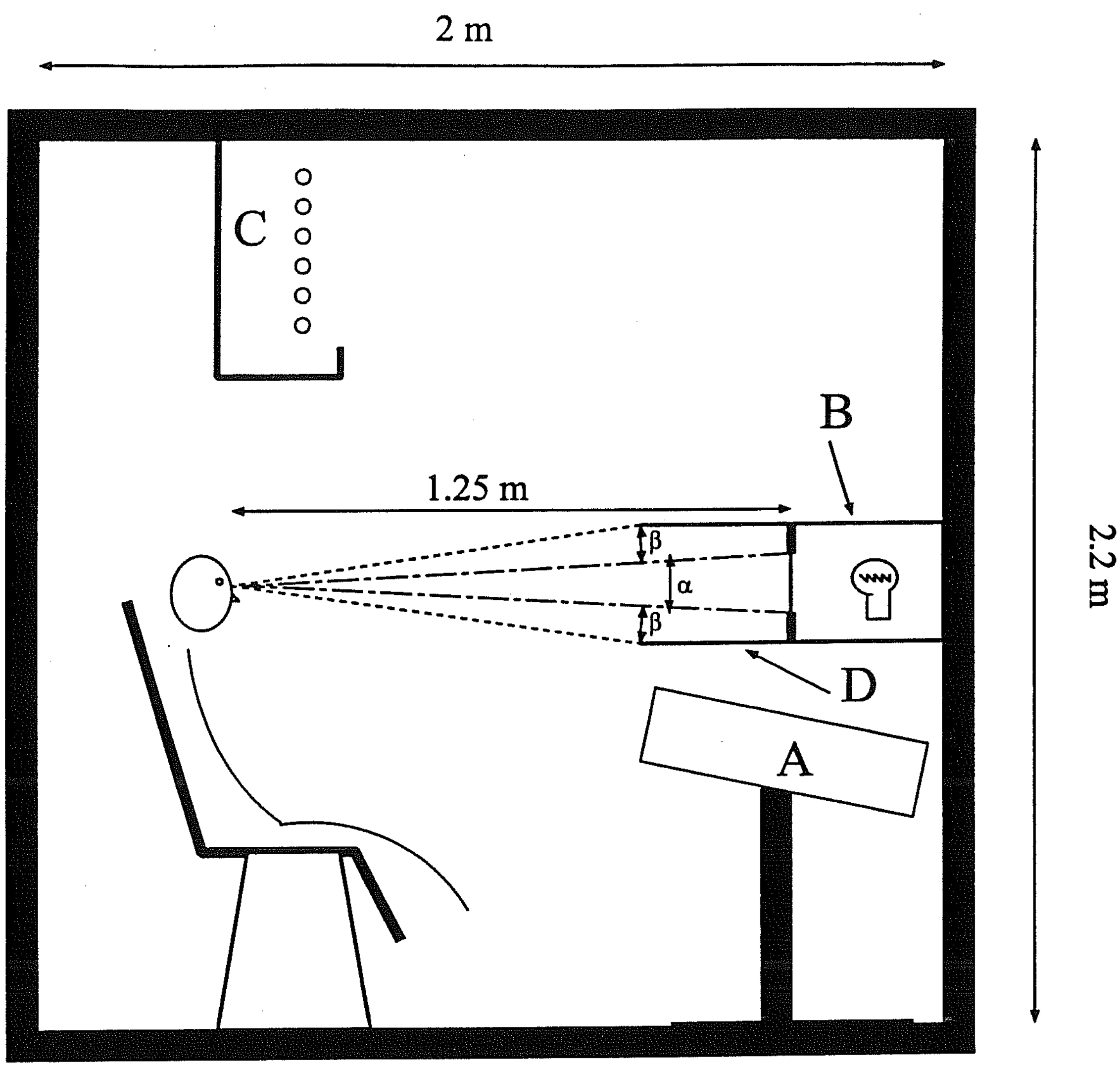


Figure 2: Photograph of experimental setup showing subject's chair, reading task box, remote pupillometer, and Pritchard photometer.

Fig. 3



A- Remote Pupillometer/Eyetracker
B- Back Illuminated Task
C- Flourescent Lamp Fixture
D- Surround Shield

α: Angle subtended by illuminated portion of task.
8.2 deg vertical
6.4 deg horizontal

β: Angle subtended by black border and surround shield
6.0 deg vertical
5.6 deg horizontal

Figure 3: Location of equipment used in the reading chart study. The reading task luminance was kept independent from the surround luminance by means of the "surround shield" (D), which subtends approximately 20 degrees.

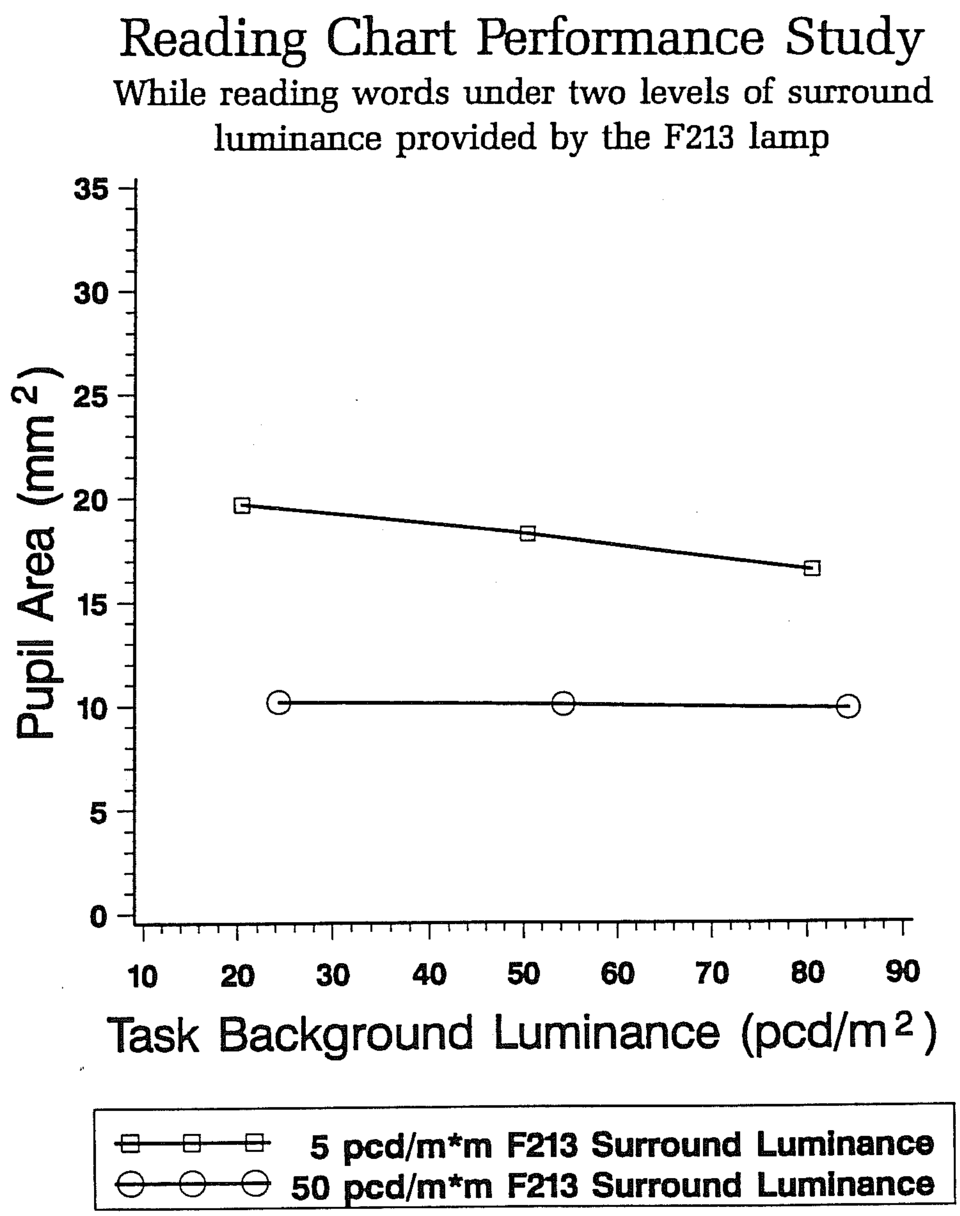


Figure 4: Graph of pupil area vs. task background luminance for the two surround luminance conditions, averaged across all subjects. Continous lines are based on a linear fit.

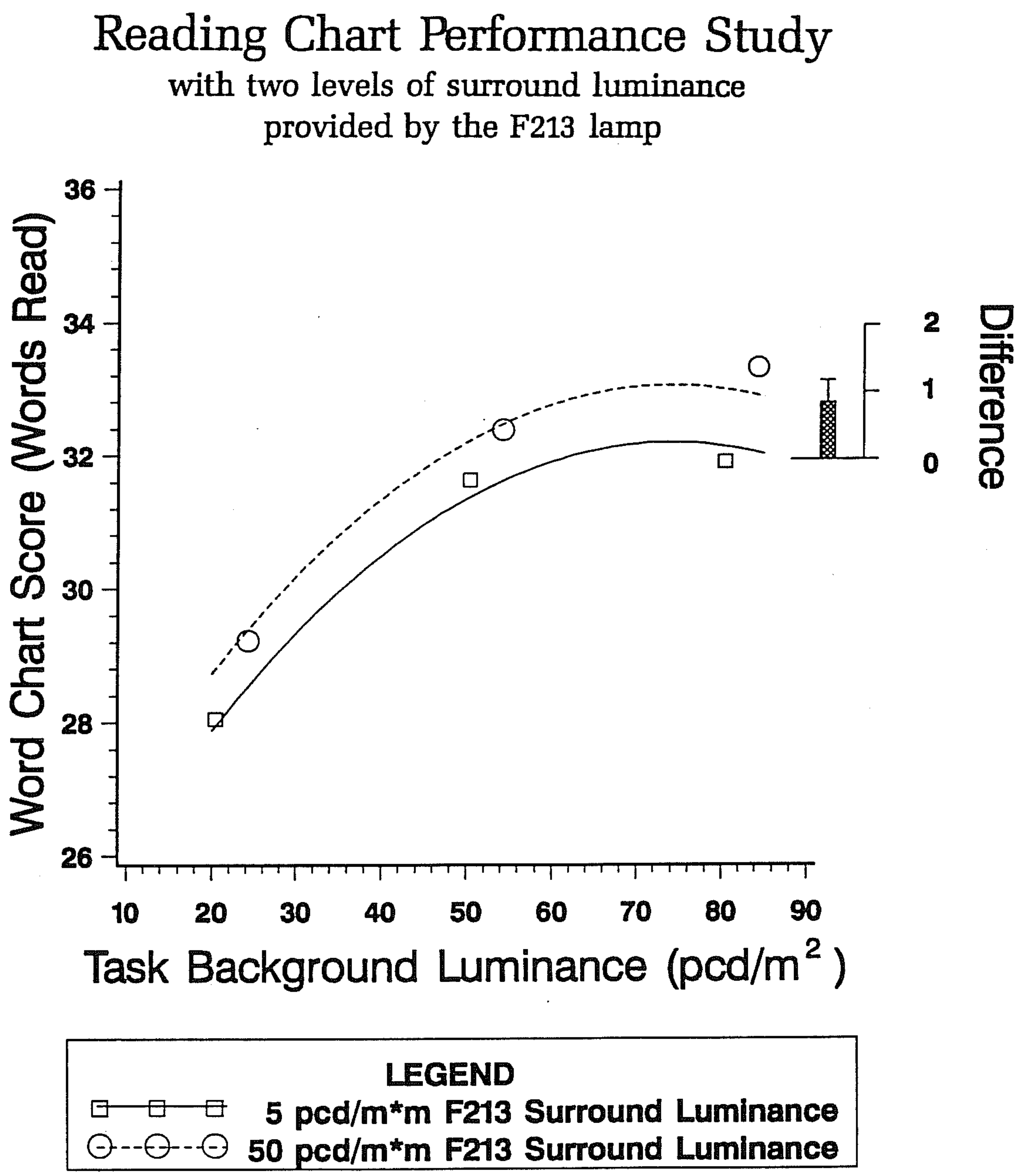


Figure 5: Graph of word chart score versus task background luminance for the two surround luminance conditions, averaged across all subjects. The right hand scale shows the mean and standard error of the score difference. The continous lines are based on a quadratic fit.

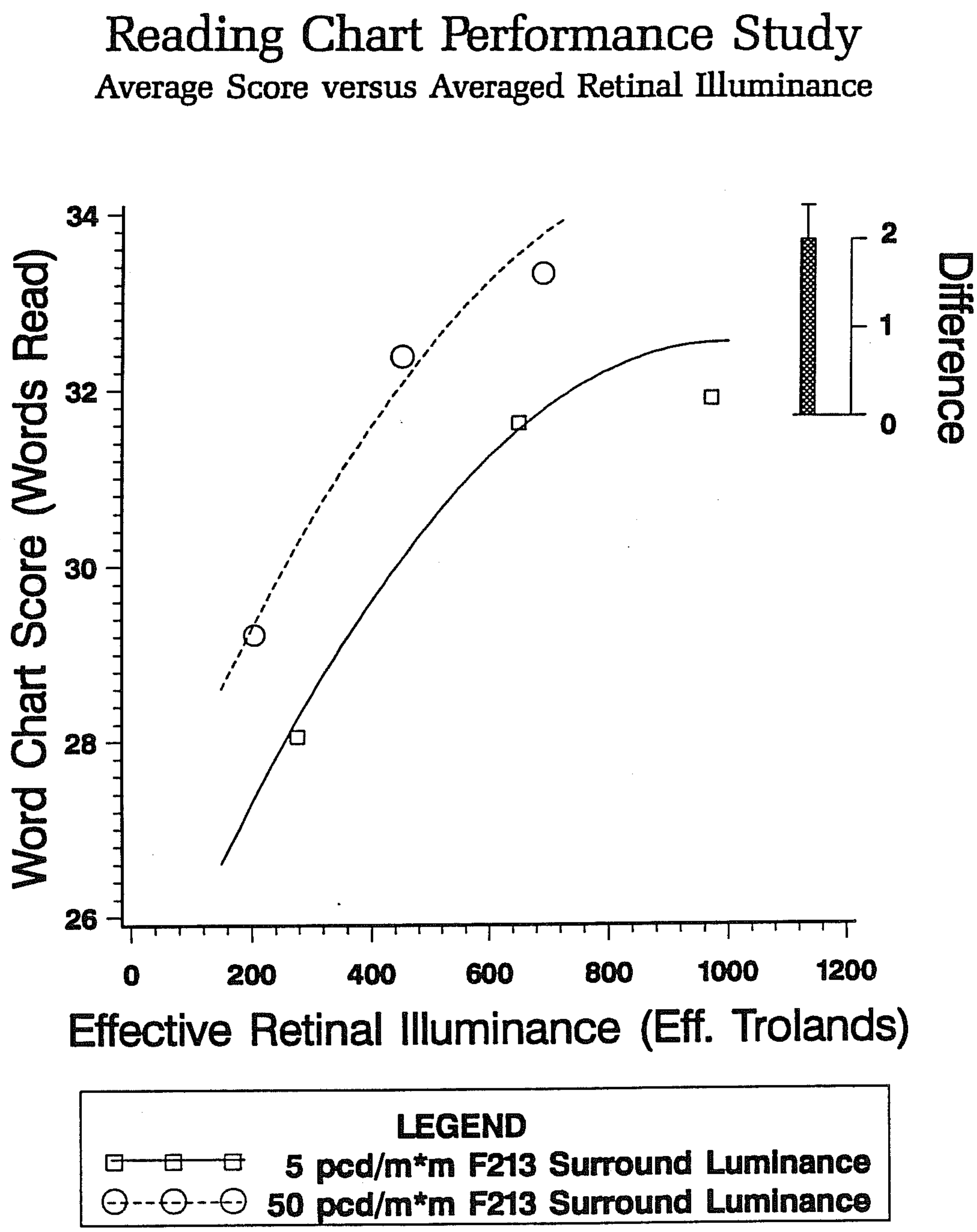


Figure 6: Graph of word chart score versus effective retinal illuminance (effective trolands) for the two surround luminance conditions, averaged across all subjects. The right hand scale shows the mean and standard error of the score difference.

Fig. 7

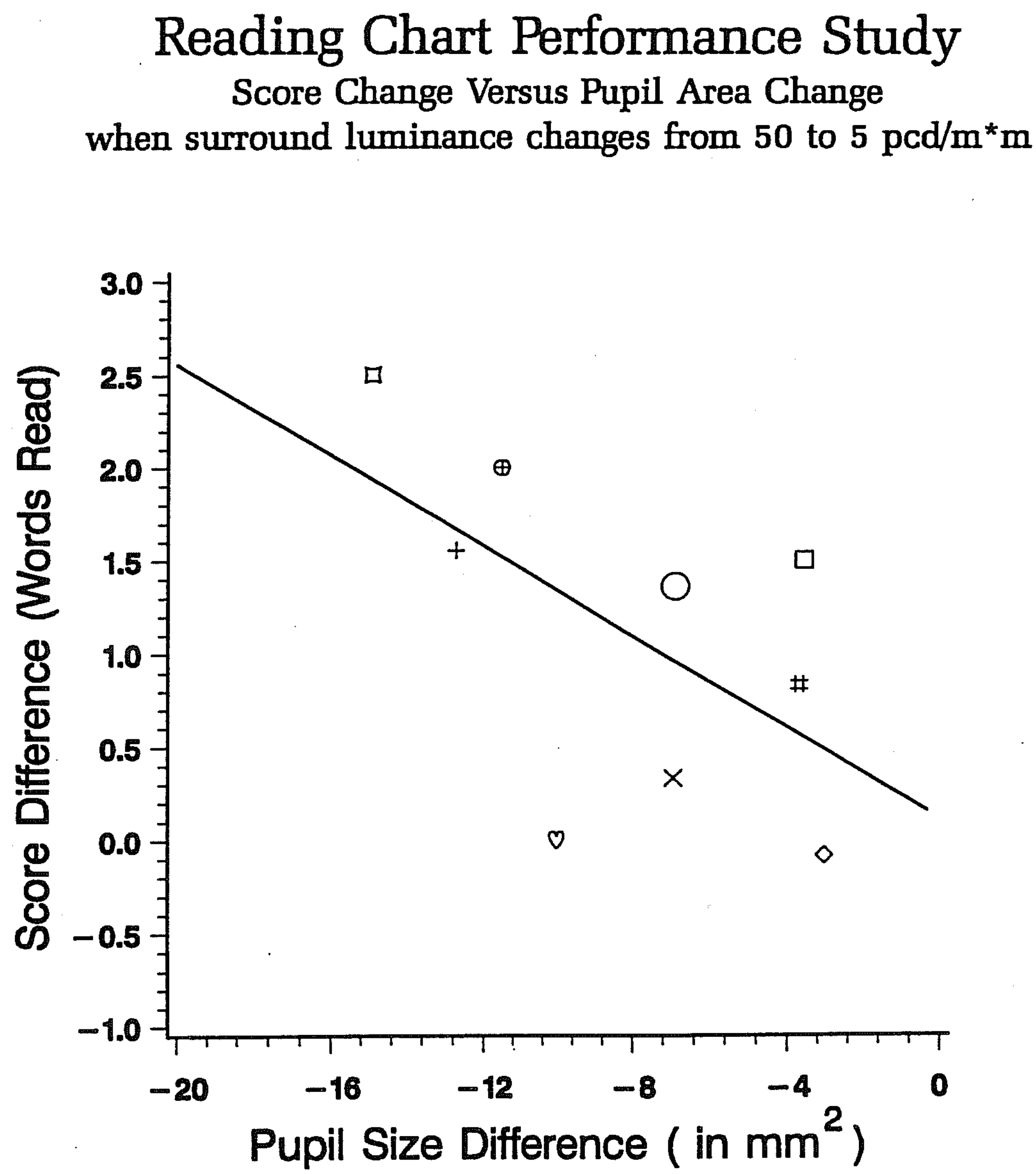


Figure 7: Graph showing trend between score difference and pupil size difference, averaged over the three task background luminance conditions. Different symbols represent the individual subjects.